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Review

Multi-GeV Laser Wakefield Electron Acceleration with PW Lasers

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Featured Application: Compact electron accelerators, Compact synchrotron source, Radiography.

Abstract: Laser wakefield electron acceleration (LWFA) is an emerging technology for the next generation of electron accelerators. As intense laser technology has rapidly developed, LWFA has overcome its limitations and has proven its possibilities to facilitate compact high-energy electron beams. Since high-power lasers reach peak power beyond petawatts (PW), LWFA has a new chance to explore the multi-GeV energy regime. In this article, we review the recent development of multi-GeV electron acceleration with PW lasers and discuss the limitations and perspectives of the LWFA with high-power lasers.

Keywords: petawatt laser; laser plasma; laser wakefield acceleration; compact electron accelerator; GeV electron beam

Citation: Kim, H.T.; Pathak, V.B.; Hojbota, C.I.; Mirzaie, M.; Pae, K.H.; Kim, C.M.; Yoon, J.W.; Sung, J.H.; Lee, S.K. Multi-GeV Laser Wakefield Electron Acceleration with PW Lasers. *Appl. Sci.* **2021**, *11*, 5831. https://doi.org/10.3390/app11135831

Academic Editor: Ci-Ling Pan

Received: 26 May 2021
Accepted: 20 June 2021
Published: 23 June 2021

1. Introduction

Laser wakefield acceleration (LWFA) has attracted much attention since it was proposed in 1979 by T. Tajima and J. Dawson [1] due to its possibility to provide a huge acceleration field for electron acceleration. Thus, LWFA can realize table-top high-energy electron accelerators and be the next generation of electron accelerators with extremely high energy over 100 GeV. However, the proposal was pending for a long time because it required too high a performance for the high-power lasers at the time. As the chirped pulse amplification (CPA) technology [2] initiated the rapid progress of high-power lasers in the 1990s, the short-pulse high-power lasers led to the realization of laser electron accelerations [3–5], albeit the quality of the electron beam was not good enough for applications. In 2004, a milestone was laid in LWFA research: a mono-energetic collimated electron beam was achieved in the bubble regime by using an intense femtosecond laser [6–8]. Since then, LWFA has been intensively investigated with high-power femtosecond lasers to provide high-quality electron beams and radiation sources [9] for practical applications to non-destructive inspections, ultrafast x-ray spectroscopy, and x-ray microscopy.

Even though LWFA can provide a huge acceleration field, some scientific and technological problems need to be solved for practical applications. First of all, LWFA uses complex nonlinear dynamics of plasma media [10], and its acceleration structure has the dimensions of tens of microns in space and hundreds of femtoseconds in time. Secondly, an intense laser pulse is modified significantly during the propagation through the plasma medium, and the modification of the laser pulse alters the plasma medium and acceleration process as a feedback loop. In addition, the electron injection into the plasma wave spontaneously happens in the plasma, which is called self-injection. Therefore, the whole acceleration process is highly nonlinear and unstable, limiting the electron energy [11,12], beam quality and stability [13,14]. Many studies are ongoing to solve these problems to improve the performance of LWFA.

The advancement of high-power laser technology is essential for the enhancement of LWFA performance. Enormous efforts have been exerted to increase the laser's peak power and they consequently succeeded in building petawatt (PW) lasers [15]. The development of PW lasers provided a chance to explore a new regime of laser particle accelerations and relativistic laser–plasma interactions. In the last decade, several types of PW lasers have been used in LWFA experiments. A PW laser was demonstrated in Texas university, Austin, by adapting the CPA to an Nd:Glass laser [16]. This hybrid laser had a very low repetition rate, below one shot/hour. The most successful demonstration of PW lasers was based on Ti:Sapphire CPA lasers. These lasers can provide laser energy over 30 J, pulse duration of about 30 fs, and a repetition rate of over 0.1 shot/second [17]. Ti:Sapphire lasers with peak power over PW have been commercialized and installed in several research institutes for relativistic laser–plasma science. As the laser power increases, the achievable electron energy by LWFA has increased by more than an order of magnitude, compared to the first demonstration of the bubble-regime LWFA in 2004. Recently, multi-GeV electron beams were obtained with a centimeter-long medium [11,18,19]; the conventional radio-frequency (RF) acceleration technology requires a few hundred meters for such beams. In addition, many applications of LWFA or radiation sources from LWFA have been demonstrated in the last decade. Therefore, LWFA has the potential for compact linear accelerators and x-ray sources as the next generation of electron accelerators.

In this paper, we review several exemplary experiments on LWFA with PW lasers. The large-scale laser facilities are installing or recently installed multi-PW lasers, e.g., the three pillars of extreme light infrastructures (ELI) [20], the Zetawatt-Equivalent Ultrashort Pulse Laser System (ZEUS) [21], the Exawatt Center for Extreme Light Studies (XCELS) [22], the Shanghai Superintense Ultrafast Laser Facility (SULF) [23], the Apollon laser [24], and the Center for Relativistic Laser Science (CoReLS) [25]. Thus, this review on the prominent experimental results on LWFA with PW lasers can be a valuable guide for the LWFA with the emerging high-power lasers.

This article is organized into five sections, as follows. We explain the fundamental physics of the LWFA process briefly in Section 2 and address the representative experimental results on multi-GeV LWFA with PW lasers in Section 3. We discuss the perspective of LWFA with PW lasers in Section 4, then we conclude.

2. Basic Physics of LWFA

In this section, we will describe the basic physical process and energy scalings of LWFA. LWFA can be realized by focusing a high-power laser pulse at a relativistic intensity above 10^{18} W/cm^2 onto a gaseous medium, as shown in Figure 1. When such an intense laser pulse interacts with a gaseous medium, the atoms in the medium are ionized at the rising edge of the pulse to turn into an underdense plasma. Thus, the main peak of the laser pulse interacts with an underdense plasma. At the laser intensity in the relativistic regime, where the normalized vector potential $a_0 > 1$, electrons in the plasma acquire a relativistic quiver velocity in the laser field. The normalized vector potential a_0 is defined as $eE_0/(m_e c\omega_0)$, where E_0, ω_0, e, m_e, and c is the laser electric field amplitude, the laser angular frequency, the electron charge, the electron rest mass, and the speed of light, respectively. When a_0 is comparable to or larger than unity, the maximum quiver velocity of a classically oscillating electron in the laser field is close to the speed of light. As the intense laser pulse interacts with the plasma, the electrons are pushed away from the laser propagation axis by ponderomotive force originated from the laser-intensity gradient of a tightly focused laser pulse. Because the electrons are expelled from the laser axis, leaving much heavier ions behind, an extremely high electrostatic field is induced by the charge separation, which acts as a restoring force for the displaced electrons. As the electrons are expelled and return to the laser axis repeatedly, periodic modulations of electron density following the laser pulse, known as a plasma wave or Langmuir wave, are created [10], as shown in Figure 1. The shape of the plasma wave can be a spherical shell [26,27], called a plasma bubble, when the a_0 is sufficiently higher than 1, and the pulse duration is shorter than half the plasma period. If an electron bunch happens to roll into the bubble by self-injection, the bunch can be rapidly accelerated in the laser propagation direction by the enormous electric field in the bubble: this field is usually stronger by three orders of magnitude than that of the conventional RF linear accelerators. As a comparison, while the current state-of-the-art linac can be driven by S-band RF having 0.1 GV/m [28], the electric field gradients from LWFA can reach as high as 200 GeV/m with a centimeter-scale plasma medium having an electron density of about 10^{18} electrons/cm^3 driven by PW laser pulses.

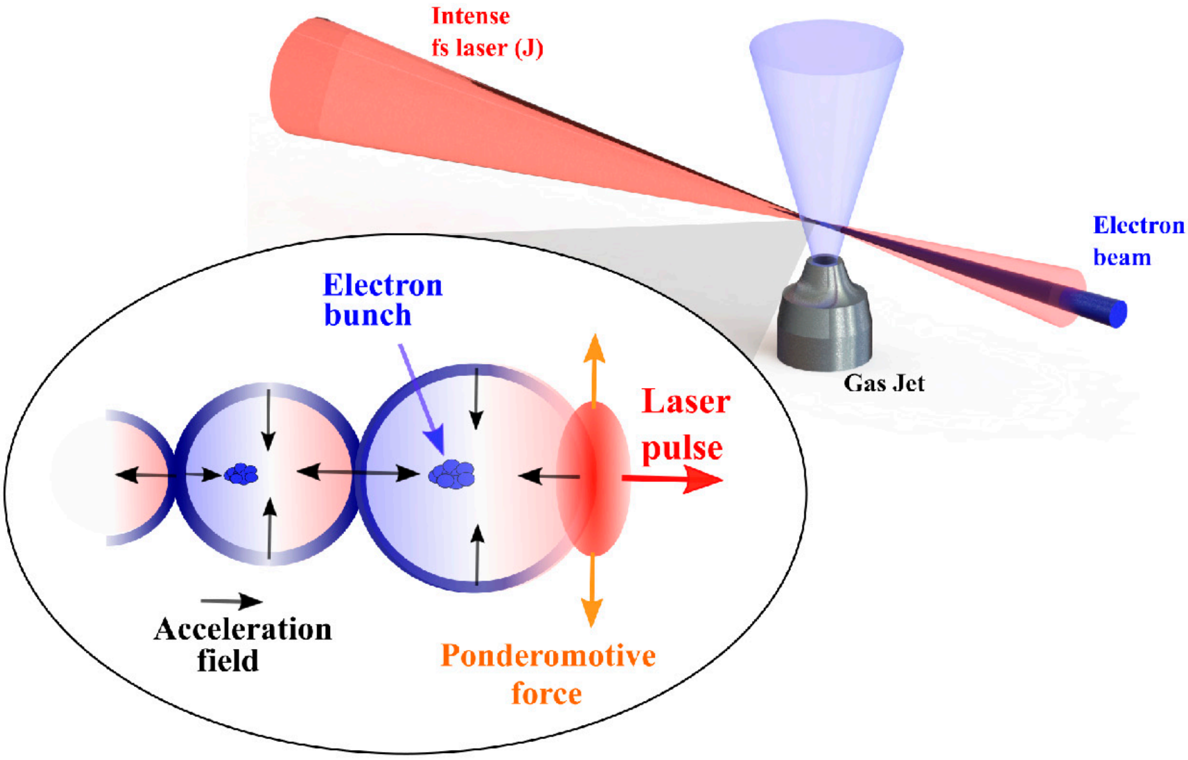


Figure 1. Schematic of LWFA process.

One of the most critical issues in LWFA is to enhance the electron energy for given laser parameters. The electron energy is limited by the effective acceleration length and the average acceleration field strength. The effective acceleration length is determined either by the laser etching (depletion) length $L_{etch} \approx (\omega_0/\omega_p)^2 c\tau_L$ or by the dephasing length $L_d = (4/3)\left(\omega_0^2/\omega_p^2\right)\sqrt{a_0}c/\omega_p$, where τ_L is the laser pulse duration, and $\omega_p = \sqrt{4\pi n_0 e^2/m_e}$ is the plasma frequency with n_0 being the plasma density. The etching length (or depletion length) denotes the distance limit of laser propagation by the loss of laser energy in plasma media. The dephasing length is the maximum acceleration length for electrons to overtake the accelerating phase of the wakefield. For a non-evolving plasma-bubble in the blowout regime, the average acceleration field strength approximately corresponds to $\sqrt{a_0}/2$ when the dephasing length is larger than the etching length, and a_0 is sufficiently larger than 1. Therefore, the achievable energy gain in LWFA for given laser power and plasma density can be given as [29]

$$\triangle E[\mathrm{GeV}] \approx 1.7 \left(\frac{P_L[\mathrm{TW}]}{100}\right)^{\frac{1}{3}} \left(\frac{10^{18}}{n_0[\mathrm{cm}^{-3}]}\right)^{\frac{2}{3}} \left(\frac{0.8}{\lambda_0[\mu\mathrm{m}]}\right)^{\frac{4}{3}} \quad (1)$$

where P_L is the peak laser power in terawatt (TW). Thus, the electron energy can be enhanced by increasing the laser power and decreasing the plasma density. However, the self-injection of electron bunches into the bubble can be prohibited when the plasma density is low, and thus, the achievable electron energy is limited at low plasma densities. In addition, the defects of the laser pulse and plasma medium can terminate the acceleration process through nonlinear processes, which are usually stronger at a higher laser power. Therefore, enhancing the electron energy by controlling laser power and plasma density is not a straightforward task.

3. Multi-GeV LWFA with PW-Class Lasers

In this section, we review several exemplary experimental results on the energy enhancement of LWFA with PW lasers. Since high-quality electron beams have been produced in the bubble or blowout regime, significant efforts have been focused on increasing the energy of the electron beam. As PW lasers are developed, the energy of the laser-driven electron beam dramatically increased to a multi-GeV regime, as shown in this section.

3.1. LWFA with Texas PW Laser

The PW laser at the University of Texas at Austin was developed by implementing the hybrid OPCPA scheme with Nd:glass laser amplifiers and had a pulse duration of 140 fs and pulse energy of 140 J [16]. The laser has been used for various laser–plasma experiments such as electron acceleration, ion acceleration, and neutron generation. Especially, the electron energy of 2 GeV was successfully demonstrated [11]. The experiment was performed by focusing the PW laser pulses with a spherical mirror having an f-number of 47 onto a 7-cm-long helium gas cell. The accelerated electron beam was dispersed by a 6.7-cm-long dipole magnet having a field strength of 1.1 T. Fiducial arrays made of tungsten wires were inserted between the magnet and the detection screens to measure the electron energy correctly. The beam cross-section at the focus was not optimal: the intensity profile was asymmetric and had several spots.

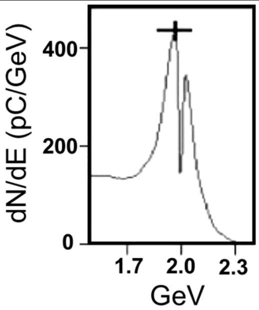
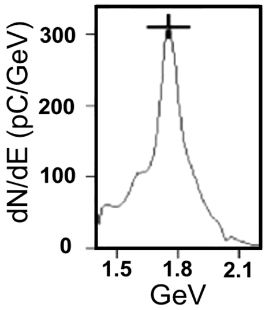
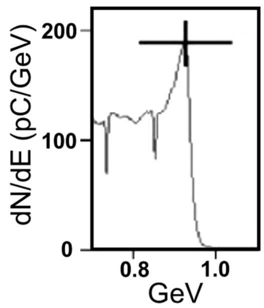
The experimental results showed that the PW laser pulses produced electron beams with energy over 2 GeV, as shown in Table 1. According to the energy formula (1), the electron energy of 2 GeV is expected for the PW laser's power and a plasma density of 5×10^{17} electrons/cm^{-3}. The electron energy was lower at lower plasma densities, which is opposite to the prediction from (1). This behavior can be attributed to the poor focal spot. A low-quality focal spot with internal structures may be beneficial to induce self-injection in such a low-density plasma but deteriorates the laser propagation and electron acceleration. It was pointed out that the spatial shaping of the PW laser pulse is necessary to enhance the electron energy.

3.2. Dual-Stage LWFA with PW Laser at UQBF

In this section, we review the dual-stage LWFA with the PW lasers at the Ultrashort Quantum Beam Facility (UQBF), Advanced Photonics Research Institute (APRI), GIST. The APRI group successfully constructed two PW beamlines in 2012 by using the CPA scheme and Ti:Sapphire amplification media. The first beamline produced energy of 30 J and a pulse duration of 30 fs [17], and the second beamline did 45 J [30] and the same pulse duration. The PW laser at UQBF was used for LWFA experiments to produce multi-GeV electron beams. As discussed in Section 2, the achievable electron energy can be increased by increasing the laser power and lowering plasma density. However, the self-injection of electron bunches into plasma waves can be prohibited by reducing the plasma density. Thus, the plasma medium density and profile should be carefully designed to maximize the electron energy: the acceleration length should be maximized while keeping self-injection occurring. One solution can be to combine gas media of different lengths and densities called dual-stage or cascaded acceleration.

The dual-stage LWFA experiments were performed by focusing the PW laser onto a dual gas jet medium consisting of 4-mm and 10-mm helium gas jets [18]. The first 4-mm helium jet acted as an injector stage, and the second 10-mm jet boosted electron energy. Laser pulses with an energy of 25 J were focused with a 4-m long concave spherical mirror, as shown in Figure 2a. The wavefront aberration of the laser pulse was corrected using a deformable mirror installed before the compressor. The laser pulse was stretched to 60 fs with a positive chirp by detuning the compressor grating.

Table 1. Experimental results for three different laser shots from the Texas PW laser [11]. Reproduced with permission from [Xiaoming Wang], [*Nat. Commun*]; published by [macmillan Publishers Limited], [2013].

Shot	a	b	c
Spectrum			
E_{peak} (GeV)	2.0 ± 0.1	1.8 ± 0.1	0.95 ± 0.1
Energy spread (%)	10	8	11
Divergence (mrad)	0.6 ± 0.1	0.5 ± 0.1	0.5 ± 0.1
Charge in peak (pC)	63 ± 8	34 ± 5	13 ± 2
Plasma density (10^{17} cm^{-3})	4.8 ± 0.1	3.4 ± 0.1	2.1 ± 0.1
Laser energy (J)	100 ± 5	120 ± 6	129 ± 6
Laser pulse duration (fs)	160 ± 10	150 ± 10	160 ± 10

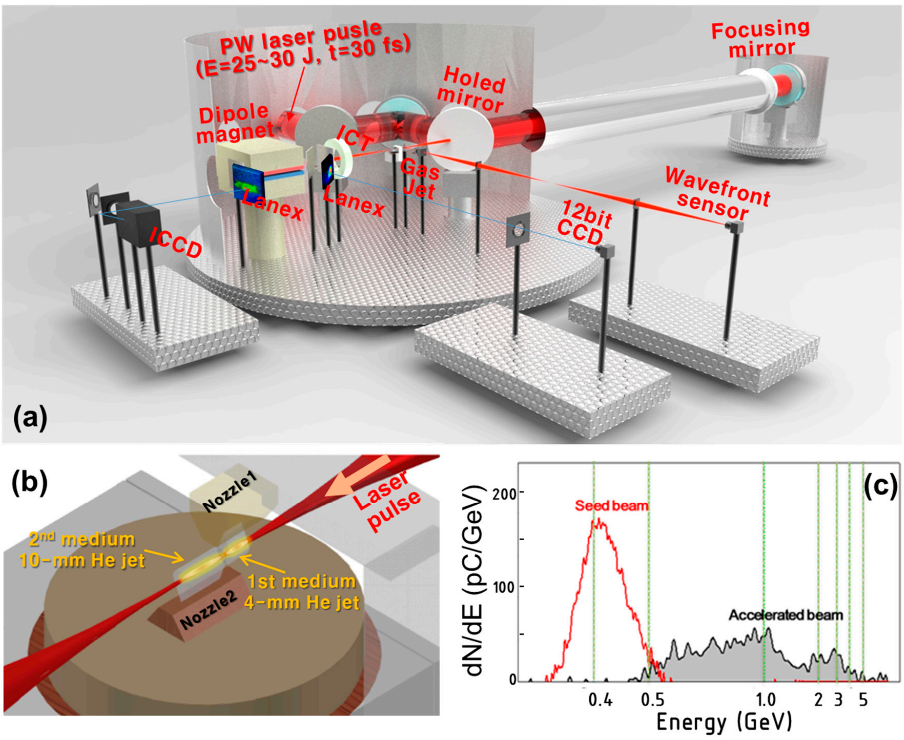


Figure 2. (**a**) Experimental layout for dual-stage LWFA with a PW laser pulse, (**b**) schematic drawing of the dual-stage target, and (**c**) the experimental result with the dual-stage target [18]. In figure (**c**), the red line shows the electron spectrum from the first target, and the black line shows the spectrum after the second target.

In the dual-stage LWFA, several issues should be properly treated to obtain a high-energy electron beam. Firstly, a self-injection should happen in the first medium, and the resulting electron bunch should have sufficient energy when entering the plasma wave in the second medium. Secondly, the electron beam and driving laser pulses should be properly coupled into the second medium. Thirdly, the electron beam should be accelerated in the second medium without an additional electron injection. The first 4-mm helium gas jet was optimized to obtain a 400 MeV electron beam by tuning the gas pressure to have an electron density of 2×10^{18} electrons/cm^3. No electron beam signal was observed when the second jet was used alone with densities below 1×10^{18} electrons/cm^3. A significant enhancement of electron energy was observed with the dual gas jet target having electron densities of 2×10^{18} electrons/cm^3 for the 4-mm jet and 0.8×10^{18} electrons/cm^3 for the 10-mm jet. The gap between the two jets was about 2 mm, and the laser focus was at the middle of the gap. At this condition, the electron bunch from the first jet could be successfully coupled to the second target because the low plasma density in the second jet enlarged the plasma wavelength to have a higher chance to catch the electron bunch from the first target. In addition, the second target having a lower density than the self-injection threshold can prohibit continuous self-injection that can reduce the acceleration field strength. When the plasma densities of the two jets were independently controlled, the electron energy was over 3 GeV. At this condition, the electron beam has a charge of about 10 pC over 2 GeV energy, energy spread about 50%, and beam divergence of about 4 mrad.

The dual-stage acceleration can be a simple solution to obtain a high-energy electron beam. Recently, a dual-stage acceleration with two driving laser pulses was demonstrated by using capillary discharge media [31]. Even though we can expect an energy gain at each stage in a staged acceleration, precise control of each stage for stability is challenging. In the dual gas jet target, the turbulence between the targets can also make the electron beam unstable. Thus, the method to handle the qualities of the accelerated electron beam should be investigated by manipulating the driving laser pulse and plasma medium. In addition, the electron energy with dual-stage LWFA was still much less than the 10 GeV that is expected for PW lasers because the laser propagation is limited to be an order of 1 cm. For increasing the electron energy further, an external guiding structure for PW laser pulses should be applied to keep the laser intensity over 10 cm.

In the dual-stage acceleration, the PW laser pulse was stretched to be positively chirped with a duration of 60 fs. It was stretched to control the acceleration gradient of LWFA by manipulating the pulse's spectral phase [32]; such a control method was demonstrated experimentally at UQBF [13,33]. In particular, positive group-delay dispersion (GDD) enhanced the energy and charge of the electron beam, and third-order dispersion (TOD) improved the energy further and the stability of the beams. The combination of a dual-stage target and careful control of laser pulse properties can be an effective way to shape the electron beams and control the acceleration process.

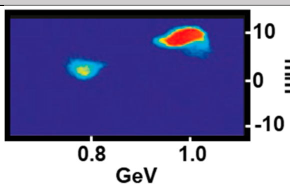
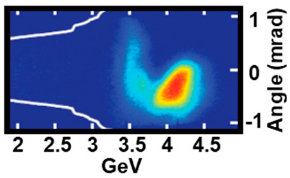
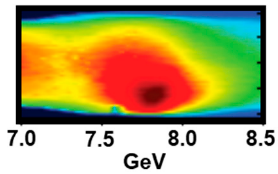
3.3. LWFA with Capillary Discharge Plasmas at LBNL

Laser propagation through a plasma medium is a highly complicated process. To increase the electron energy for a given laser power, the elongation of laser propagation is a critical issue in LWFA research. Most experiments were performed with self-guiding schemes that provide a much longer propagation length than the Rayleigh range by balancing relativistic self-focusing and diffraction. For increasing the electron energy, the plasma density should be lower, and the medium length should be longer. However, the elongation of laser-propagation length by relativistic self-guiding is getting more difficult as plasma density is lowered because the critical power for self-guiding increases as the plasma density decreases. Thus, the elongation of the laser propagation through the plasma medium is an essential technique to increase electron energy with PW laser pulses. One of the solutions is guiding the laser pulse with a plasma channel. The plasma channel guiding utilizes a refractive index gradient in the transverse direction like optical fibers.

It can contain high-intensity laser pulses in the relativistic regime due to the extremely high-intensity limit of the plasma medium. Several groups developed plasma channel technology [34–36], and the research group at Lawrence Berkley National Laboratory successfully applied the plasma channel to enhance the electron energy [16,32,33].

The first successful application of a plasma channel to LWFA demonstrated 1 GeV electron acceleration by focusing a 40 TW laser pulse to a 3.3 cm plasma channel [37]. The plasma channel was formed in a pre-ionized hydrogen plasma confined in a capillary tube. The capillary tube was fabricated on a sapphire block by laser machining: two gas inlets and a central tube with a few-hundred-microns diameter. The hydrogen gas was fully ionized by a high-voltage electric pulse applied to the electrodes at both ends of the capillary tube. The pre-formed plasma had a hyperbolic electron density profile in the transverse direction that can guide an intense laser pulse. The capillary discharge medium has an obvious advantage of elongated laser propagation through the plasma medium. Table 2 summarizes the successful demonstrations of electron energy enhancement with capillary discharge plasma channels and sub-PW [19] and PW lasers [12].

Table 2. Characteristics of electron beams from capillary discharge plasma channel and experimental condition for three different experiments with laser power of 40 TW [37], 300 TW [19], and 850 TW [12]. Reproduced with permission from [Leemans, W.P], [*Nat. Phys*]; published by [Nature Publishing Group], [2006].

	Experiment 1	Experiment 2	Experiment 3
Spectrum			
Channel length (cm)	3.3	9	20
Plasma density (10^{17} cm^{-3})	43	7	3.4
Laser power (TW)	40	300	850
Laser pulse duration (fs)	40	40	40
E_{peak} (GeV)	1	4.2	7.8
Energy spread (%)	1.6 (r.m.s.)	6 (r.m.s.)	~10 (FWHM)
Divergence (mrad)	1.6 (r.m.s.)	0.3 (r.m.s.)	0.2 (FWHM)
Charge in peak (pC)	~30	6	5

The enhancement of electron energy with the laser power is not straightforward, even though the plasma channel can guide the driving laser pulse to a long distance. Since 1-GeV electron beam was produced with a laser power below 100-TW, as seen in experiment 1 in Table 2, a 1-PW laser pulse should have the capability to generate a 10-GeV electron beam. Despite the use of sub-PW laser pulses, a 4.2-GeV electron beam was produced with a 9 cm capillary discharge plasma channel because of the nonlinear evolution of laser pulses with a top-hat profile. The nonlinear propagation in the plasma can assist the self-injection process but disturb smooth laser propagation in the plasma channel. For increasing electron energy in LWFA further, a longer laser propagation through a plasma with a lower plasma density is essential. However, the nonlinear laser propagation can prohibit the increase of electron energy by limiting long and smooth laser propagation through a plasma medium with an extremely low electron density below 5×10^{17} electrons/cm^3. Although experiment 2 in Table 2 was performed with an almost perfectly focused laser beam of Strehl ratio of about 0.8, the top-hat laser profile in the near field, ordinarily formed by the laser amplification, induced a nonlinear laser propagation and hindered the additional increase of electron energy.

The nonlinear laser propagation problem has been mitigated by steepening the transversal electron density gradient of the plasma channel. A nanosecond laser, focused on the axis of the discharge capillary plasma channel, heated through inverse bremsstrahlung the core of the capillary discharge plasma channel and created a deeper electron density valley that could guide a PW laser pulse efficiently. Thus, the effect of the nonlinear laser propagation could be mitigated, and the laser pulse could propagate tens of centimeters in a plasma channel with an electron density of 3×10^{17} electrons/cm^3. This improvement of laser propagation by a steepened plasma channel made it possible to generate the most energetic electron beam of about 8 GeV from LWFA (experiment 3 in Table 2). This result implies that engineering the plasma medium is a key to realizing the maximum electron energy expected by the power-scaling of the electron energy. Consequently, more and more efforts should be exerted to control the plasma medium, not only to increase laser power but also to find suitable electron acceleration conditions for high-energy electron beams by LWFA.

4. Perspective of LWFA with PW Lasers

In this section, we will discuss the current difficulties of LWFA with PW lasers and the future perspective of LWFA with upcoming multi-PW lasers. We reviewed several experimental results on LWFA with PW laser pulses. Overall, PW lasers demonstrated multi-GeV LWFA in the energy range from 2–8 GeV with divergence of about 1 mrad, the beam charge in the order of 10 pC, and energy spread of about 10%. The rapid progress of high-power lasers enabled the development of high-energy electron beams with high bunch charge and small beam emittance. Although PW lasers began to appear a decade ago, and the expectations on LWFA have been quite promising, experimental results were relatively rare. The advancement of LWFA with PW lasers was retarded due to the technological difficulties in operating PW lasers and the growing complexity of experimental setups. LWFA uses highly nonlinear processes in a plasma medium with micrometer scale acceleration structures. Thus, tiny defects of laser pulses and the plasma media can significantly deteriorate the acceleration processes. As laser power and system size increase, the elimination of the flaws is getting more difficult.

The recent development of high-power laser reached 10 PW peak powers [38], and 100-GeV electron acceleration with LWFA is not an absurd goal. However, the massive scale of the LWFA experimental system with the 10-PW lasers can make it challenging to realize a 100-GeV electron beam. From the estimation with Equation (1), a 10-PW laser with 250 J energy can produce a 100 GeV electron beam by focusing the laser pulse with F/# > 150 onto a 10-m length plasma medium with an electron density of about 10^{16} electrons/cm^3. If the beam size of the 10 PW laser is about half a meter, then the LWFA experimental system, including the focusing system, acceleration medium, and detection system, should be more than 100 m to achieve 100 GeV. The 10 PW laser should have the beam pointing stability below 1 μrad before the focusing mirror for its pulse to be properly guided along the 10-m plasma channel. The plasma medium also has to be well designed and fabricated to be transversally profiled for a deep electron density gradient to guide the 10-PW laser pulse with a longitudinal uniformity over 10 m. For that reason, engineering efforts should be devoted to constructing more stable 10-PW lasers with a clean focal spot as well as a long plasma channel medium with substantially profiled electron density distribution.

The electron injection at such a low electron density is problematic. The self-injection process occurs when the laser intensity and the plasma density are high enough to induce the wave breaking of the plasma wave. The self-injection, empirically, happens when the laser power is higher than the critical power, $P_c \approx 17 \left(\frac{\omega_0}{\omega_p}\right)^2$ GW [29]; that is, the laser power where relativistic self-focusing dominates over diffraction. For the plasma with an electron density of 10^{16} electrons/cm^3, the critical power is about 3 PW. However, the laser pulse duration should be stretched to be more than 150 fs to prevent too quick etching, and the laser power on target would be below 2 PW. At this condition, self-injection is not possible. Recently, electron injection mechanisms, such as ionization injection [39–41], density shock injection [42,43], and nanoparticle insertion [44,45], have been proposed and demonstrated. Because the laser should propagate 10 m for 100 GeV acceleration, the electron injection process should not degrade laser properties and should occur only at the beginning of the medium. Thus, the electron injection mechanism for 100 GeV LWFA should be chosen carefully to maintain the laser quality and induce localized injection at the beginning.

The nanoparticle insertion method can be promising as an injection method for achieving 100 GeV by LWFA because nanoparticles can induce an electron bunch with a sufficient charge at extremely low plasma density close to 10^{16} electrons/cm^3 while making negligible effects on laser propagation due to its tiny size, much smaller than the laser wavelength. A nanoparticle in plasma medium for LWFA can induce a highly localized injection, leading to an electron beam with a small emittance. A numerical study showed that a nanoparticle in plasma could facilitate a controllable injection to produce a high-quality 5-GeV electron beam with a 0.5-PW laser pulse [44]. Furthermore, a recent experimental study demonstrated nanoparticle-assisted laser wakefield acceleration with a nanoparticle-mixed helium gas jet [45]. Although controlling precisely the location of nanoparticles in plasma is challenging, the nanoparticle injection method can be a promising method to realize a 100-GeV electron beam with 10-PW-class lasers.

An alternative way to increase the energy gain of LWFA is to use an intense two-color laser pulse [46]. A recent numerical study with particle-in-cell simulations showed the feasibility of all-optical staging of LWFA using a two-color laser pulse train: a fundamental laser pulse induces an electron injection, and the subsequent second harmonic pulse accelerates the injected electron bunch to high energy. The theoretical study showed the possibility of achieving 10 GeV with a-few-PW lasers and a-few-centimeter-long plasmas. It was suggested that the two-color scheme might achieve 100 GeV with the near-future state-of-the-art lasers having power in the range of 10 PW.

In addition to control of injection and increasing the laser power, other technical challenges of plasma media and laser controls need to be addressed. The structure of the acceleration medium needs careful consideration, thus shaping the density profile over long distances is required. For example, the use of density up-ramp medium [47] or multi-jets configuration [48] has been recently employed, albeit they have been done in a low laser power regime and with short distance. The careful shaping of the profile can produce beams with energy spread below 1% [49]. We, thus, foresee that longitudinal control of the plasma density profile over a wide density range (10^{14}–10^{19} cm^{-3}) is a necessity for improving the energy and quality of electron beams produced with multi-PW lasers. While longitudinal control of the density profile seems the major challenge for improving PW-laser-based acceleration, advances in various guiding methods and technologies will provide additional improvement of the acceleration process. Besides the challenge of producing stable long-distance channels [50], curved channel technology will provide a useful method to control the directionality of electron beams and laser pulses [51]. In addition, recent theoretical and numerical studies proposed to overcome the dephasing length of LWFA, so-called phase-locked [52] or dephasingless [53] LWFA, by adapting the superluminal velocity of focal spot movement [54], which can be a way to maximize electron energy for given laser power.

LWFA is considered a promising electron acceleration technology that may overcome the limitations of the current RF linear accelerators, despite the drawbacks such as the bulky systems of lasers with peak powers beyond PW and sophisticated acceleration processes. Upcoming laser systems having a peak power beyond 10 PW have the potentials to enhance the electron energy more than an order of magnitude, even close to TeV electron energy, which can initiate a new horizon of fundamental physics. For a new era of particle physics with LWFA, developments of two technologies are essential; one is precise control with sub-micron accuracy of the upcoming high-power lasers with peak power of 10–100 PW, and the other is profiled plasma channels over 10 m. In addition, proposing and demonstrating new schemes of electron injection and acceleration processes, such as nanoparticle injection, two-color LWFA, and dephasingless LWFA, should be pursued.

5. Conclusions

We reviewed the progress of LWFA with PW lasers in the last decade. The Texas PW laser was successfully applied to LWFA and produced 2 GeV electron beams, while the acceleration was limited due to the poor focal spot. The PW laser at UQBF demonstrated a 3-GeV electron beam by a dual-stage acceleration scheme. The electron energy in the dual-stage LWFA was still below what is expected for PW lasers due to short laser propagation without a guiding structure. The most successful experimental results of LWFA with PW lasers have been obtained by using a capillary discharge plasma channel by the Berkeley group. Although the plasma channel can guide a PW laser pulse, the nonlinear laser propagation in the plasma channel can limit the acceleration length and electron energy. The nonlinearity in laser propagation was suppressed by deepening the plasma channel by collisional heating of the plasma channel core with a nanosecond laser. As a result, a 7.8-GeV electron beam was produced with a PW laser pulse and the capillary discharge plasma channel. In the last decade, the advent of PW lasers brought the expectations of rapid progress in LWFA research, but the development of LWFA in this new regime has been retarded by technological barriers. In the upcoming decade, 10–100 PW lasers will be constructed and used for electron acceleration by LWFA. Suppose the plasma medium and the laser propagation are controlled over about 10 m along the propagation direction and at the precision of micrometers in the transverse direction. In that case, the LWFA with PW lasers will break the limit of the conventional RF accelerations.

Author Contributions: H.T.K. wrote the draft. H.T.K., V.B.P., C.I.H., M.M., K.H.P., C.M.K., J.W.Y., J.H.S. and S.K.L. reviewed and edited the manuscript. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by the GIST Research Institute (GRI) grant funded by the GIST in 2021, Ultrashort Quantum Beam Facility (UQBF) operation program (140011) through APRI-GIST, the National Research Foundation of Korea (NRF) grant funded by the Korea gov-ernment (MSIT) Grant No. NRF-2020R1F1A1070538, and the Institute for Basic Science, Korea (IBS-R012-D1).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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